AD-A070 007 SHEFFIELD UNIV (ENGLAND) DEPT OF CHEMICAL ENGINEERIN--ETC F/G 21/2
MEASUREMENT IN MULTIPHASE REACTING FLOWS - A REVIEW,(U)
JAN 79 N A CHIGIER AFOSR-77-3414

UNCLASSIFIED AFOSR-TR-79-0657 NL

1 OF 1

AD
A070007

END
DATE
FILMED
7-79
DDC

79-0082

Measurement in Multiphase Reacting Flows—A Review

N.A. Chigier, *University of Sheffield, UK*

17th AEROSPACE SCIENCES MEETING

New Orleans, La./January 15-17, 1979

[redacted]

MEASUREMENT IN MULTIPHASE REACTING FLOWS

Norman A. Chigier*
Department of Chemical Engineering and Fuel Technology
University of Sheffield, Mappin Street, Sheffield S1 3JD, England

Abstract

A survey is presented of diagnostic techniques and measurements made in multiphase reacting flows. The special problems encountered by the presence of liquid droplets, soot and solid particles in high temperature chemically reacting turbulent environments are outlined. The principal measurement techniques that have been tested in spray flames are spark photography, laser anemometry, thermocouples and suction probes. Spark photography provides measurement of drop size, drop size distribution, drop velocity, and angle of flight. Photographs are analysed automatically by image analysers. Photographic techniques are reliable, inexpensive and proved. Laser anemometers have been developed for simultaneous measurement of velocity and size of individual particles in sprays under conditions of vaporization and combustion. Particle/gas velocity differentials, particle Reynolds numbers, local drag coefficients and direct measurement of vaporization rates can be made by laser anemometry. Gas temperature in sprays is determined by direct *in situ* measurement of time constants immediately prior to measurement with compensation and signal analysis by micro-processors. Gas concentration is measured by suction probes and gas phase chromatography. Measurements of particle size, particle velocity, gas temperature, and gas concentration made in airblast and pressure atomised liquid spray flames are presented.

1. Introduction

Measurements in particle-laden flames can either be made by the insertion of probes or by noninvasive optical means, generally using lasers as the source of light. Many instruments which have proved satisfactory for making measurements in purely gaseous flames cannot be used directly in multiphase reacting flows. Delicate probes are physically damaged by impaction of particles; orifices in probes can become clogged or partially blocked; deposition of particles on sensors can change their characteristics; and many gas analysis systems cannot tolerate the presence of particulate matter. The use of such probes is only possible if the particles are prevented from entering the probe or if they are collected and separated from the gaseous flow once they have entered the probe. Despite the many attempts which have been made to overcome these problems, most of the solutions are not completely satisfactory. Particulates continue to cause both difficulties in making the measurements and inaccuracies in the final results.

Amongst the intrusive techniques, the microthermocouple causes minimum disturbance. By directly linking the output from fine wire thermocouples to a computer, measurements of local time constants are made, followed immediately by direct digital compensation. Measurement of the time-dependent local gas temperature can be made in flames with particulates. Measurement of gas concentration and physical and chemical analysis of particles is made by suction probes fitted with filters to allow separation of particles and gas. Concentration measurements of gas species are made by chromatography, chemiluminescence and flame ionization.

Optical diagnostic techniques are specially desirable in particle-laden reacting flows. For making measurements in highly turbulent, nonuniform, heterogeneous conditions existing in practical combustors, many of the classical optical methods, requiring integrations over long optical paths, are unsatisfactory. Continuous wave and pulsed laser light sources provide high energy, monochromatic, coherent beams of photons, which can be focused on to small volumes of the order of 1 mm^3 within the combustor. The presence of particulates affects the scattering of the light from laser probes, so that special developments and instrument technology are required in order to utilize these probes in particle-laden flames. The laser anemometer has proved to be the most successful instrument for making simultaneous measurements of velocity and size of individual particles. The high frequency response of this instrument allows measurement of fluctuations in particle size and velocity as a function of time by use of electronic signal processing and analysis by high-speed computer.

This survey includes a review and discussion of the state of the art of spark photography, laser anemometry, and measurements by thermocouple and suction probes. A selection of measurements of drop size, drop velocity, and temperature and gas concentration in spray flames is presented. Problems and difficulties encountered with these measurement techniques are discussed. Indications are given of directions to be followed for future development of noninvasive laser optical techniques.

2. Spark Photography with Automated Analysis

Shadow photomicrography with high intensity spark light or laser sources has been used extensively for measurement of spray characteristics. One of the major problems in the application of automated image analysis techniques to the analysis of spray photographs has been the determination of the extent to which photographic images of particles are in focus. This problem has been solved by calibration of properties of particle images as functions of the particle diameter and the position of the particle in the field of view of the camera. This calibration is incorporated in the program of the image analysis computer and permits the selection of only those images which have been determined to be in focus by calibration.

The optical system for spark photography of fuel sprays is shown in Fig. 1. The spark unit, operating at 10 kV, is either focused on a 1 mm dia. aperture to provide a point light source, or, alternatively, the aperture is replaced by a diffusion screen which effectively reduces the depth of field when high density sprays are studied.

* Associate Fellow AIAA

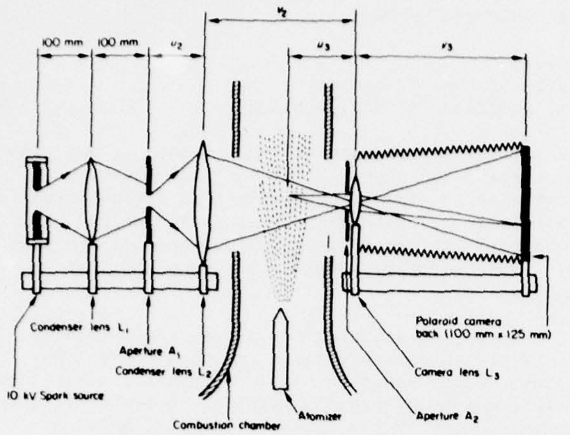


Fig. 1 Optical geometry for spark photography of fuel sprays[9]

Table 1 shows values of the optical parameters which have been used to photograph ultrasonically and airblast atomised liquid fuel sprays. Polaroid photographs are taken at various locations within the spray.

TABLE 1
Optical geometries used to study different sprays

Type of spray	Low throughput ultrasonically atomized kerosene, water or heavy fuel oil	Air blast atomized kerosene or steam blast atomized heavy fuel oil	Heavy fuel oil, off-design conditions, atomized by cold air, high throughput
Particle dias. of interest (μm)	7–90	15–300	70–900
Mass median dia. (μm)	25	80	350
Camera magnification	11	5	1
Measurement depth of field (mm)	1	3	10
Light source	point	point	diffusion screen
Dia. of lens L_2 (mm)	80	120	95
Foc. length of L_2 (mm)	80	220	150
v_2 (mm)	300	490	1050
Foc. length of L_3 (mm)	90	150	360
u_3 (mm)	100	180	720
v_3 (camera length) (mm)	1100	900	720

Each photograph is analysed by the image analysis computer, shown in Fig. 2. Photographs are scanned by a plumbicon video scanner via an epidiascope, or alternatively, a microscope. Negatives are used so that the shadow images of particles appear as bright areas on the television screen, and any dust particles on the negatives appear as dark areas. The video signal is digitized to give a measurement of light intensity in a matrix of 700 x 1000 'picture points'. The magnification of the lenses between the photograph and the plumbicon scanner is chosen to suit the smallest images which are to be measured in the photograph. The program selects only those images which are sufficiently in focus to be within a chosen measurement depth of field. When sufficient images have been measured, plots of particle number and volume size distributions, calculated numerical, mass and Sauter mean diameters and particle shape information are printed out.

Particles down to 5 μm in diameter have been photographed moving at speeds of 30 m/s in flames. Under luminous flame conditions, light filters are introduced so as to reduce the effect of background lighting. On average, 100 to 200 particles are counted per photograph within the 10 mm depth of

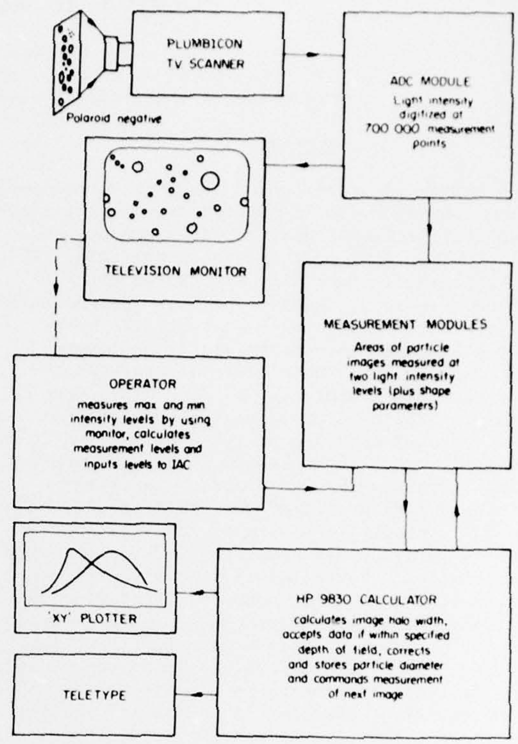


Fig. 2 Image analysis computer for automated analysis of spark photographs[9]

field. Measurement of approximately 1000 particles is required in order to derive the mass median diameter to within 5% and to produce a repeatable histogram of particle sizes. On average, 25 minutes is required to derive a size distribution for one position in a spray from 8 photographs, including the time required to print the cumulative measurements. The time required to expose and develop photographs is typically 15 minutes. The total experimental time required to derive a size distribution for one position in a spray is approximately 40 minutes. Figure 3 shows size distributions measured by the image analysis computer for three different sprays, with particles ranging from 7 to 800 μm in diameter. Data are plotted as mass distributions in 'Rosin-Rammler' form.

The photographic technique was used for measuring the size, velocity and angle of flight of droplets in pressure jet hollow cone liquid sprays injected into uniform airstreams[1,2]. The development of the technique for making measurements in flames[3] led to studies of spray flame characteristics in twin-fluid atomisers[4] and pressure jets injected into the wake of a stabilizer disk[5]. This study showed the aerodynamic interaction between sprays and recirculation zones[6]. The measurement technique is described[7] and a comparison of the dynamics of droplets in burning and isothermal kerosene sprays is shown in Ref. 8. The automated analysis of spark photographs for measurement of particle sizes and sprays is described in detail in Ref. 9.

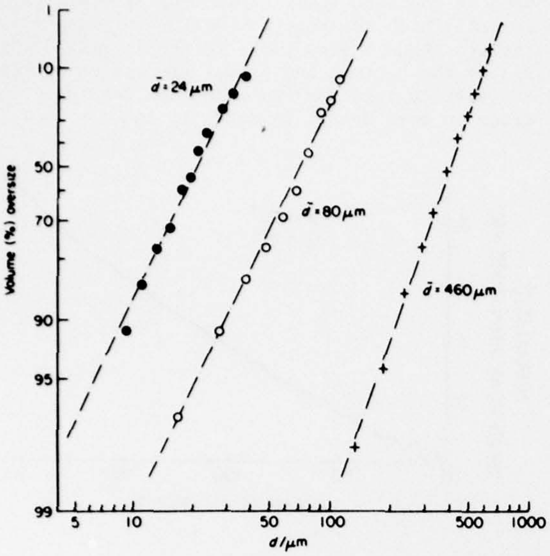


Fig. 3 Size distribution measured by image analysis computer for a range of sprays:
● - ultrasonically atomised kerosene, 5 kg h^{-1}; o - airblast atomised water, 13 kg h^{-1}; + - airblast atomised heavy fuel oil, 1000 kg h^{-1}; ·—·— - Rosin-Rammler empirical lines[9]

Spark photography is, at present, one of the most accurate and least expensive techniques for particle analysis. The technique allows direct measurement of size, shape, velocity and angle of flight of individual particles, from which distributions throughout the spray can be determined of local number density and local size distribution. The basic photographic technique has been extended by the following means: (1) Use of television cameras and video tape to record images and carry out subsequent analyses by image analysis computer. These two operations can be directly coupled so as to provide on-line image analysis. (ii) Replacement of spark sources by pulsed lasers, so as to provide shorter duration light sources with more uniform background lighting. This allows particles to be measured more accurately down to a size of 2 μm. (iii) Holography in conjunction with a pulsed laser. A single hologram covers a wide depth of field. By reconstructing this hologram, using a television camera, the sections of the spray can be brought into focus under controlled conditions, allowing more detailed analysis of the spray.

3. Laser Anemometry

Laser anemometry has been developed for the simultaneous measurement of droplet size and velocity. Signals are recorded of light scattered by individual particles as they cross the fringes in the measurement volume formed by the crossing of two laser beams. The velocity of particles is determined directly from the analysis of the measurement of frequency from the modulated signal. The intensity of the scattered light is a function of the particle size. Provision needs to be made for optical access to allow either the forward-scatter or back-scatter modes of dual beam anemometry to be utilized. Measurements of velocity components, turbulence intensity, correlations and spectra have been made in a wide range of flames on both laboratory and industrial scales. In many combustion systems, there is a sufficient amount of particulate matter to enable velocity measurements to be made, but improved signal-to-noise ratios have been achieved by seeding the gas flows with micron-size particles, such as magnesium oxide. Spatial resolution is generally of the order of 2 mm length by 200 μm diameter and frequency response in the kHz range has been achieved by sufficient seeding. Amongst the several signal diagnostic techniques, the single particle counter has been favoured, in that it provides an accurate measurement of velocity of individual particles. Velocity variations with time can be determined, enabling conditional sampling and detection of large-scale eddy movements.

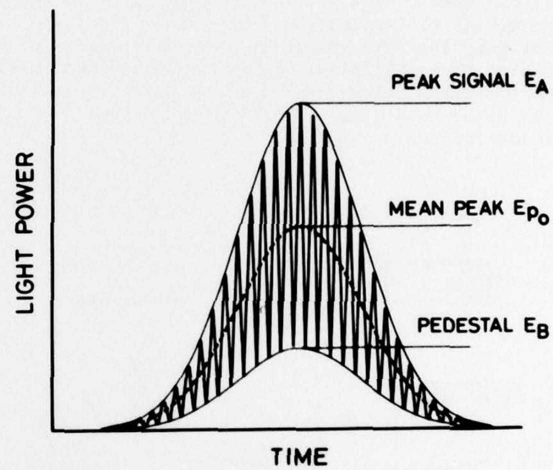


Fig. 4 Doppler signal for simultaneous particle size and velocity measurement[12]

The Doppler signal for a single particle passing through the centre of the measurement control volume of a forward-scatter laser anemometer system is shown in Fig. 4. The signal is composed of a Gaussian distribution for the pedestal and the envelope. The mean of the signal is determined electronically and the mean peak E_{P_0} is determined as a function of particle size for a fixed optical arrangement. Calibrations of individual particles attached to rotating disks traversed through the centre of the measurement volume demonstrated that, by judicious selection of the optical geometry, an unambiguous one-to-one relationship could be obtained between the amplitude of the low pass filtered mean signal and the particle diameter for particles in the range 30 to 240 μm. Predictions based on a combination of refraction, reflection and diffraction of the incident light were found to be in good agreement with these measurements[10,11].

The nonuniform light intensity within the measurement control volume (MCV) results in a variation of signal amplitude with particle trajectory through the MCV. Particles which do not pass through the centre of the MCV produce lower amplitude signals, which cannot be simply distinguished from signals produced by smaller particles passing through higher light intensity regions of

the MCV. This ambiguity effect has been taken into account by using an inversion routine to convolute the signal amplitude distributions obtained from many particles, by using the equation relating the signal peak to both particle diameter and particle position in the MCV. This data conversion method involves the inversion of a near-singular matrix or, alternatively, utilization of an iterative curve fitting technique. One method of overcoming this ambiguity, due to variation of light intensity along the axis, is to introduce an additional 'gate' photomultiplier at 90^{o} to the optical axis. The data processing system is modified so that the signal from the forward direction photomultiplier is only measured when the signal is simultaneously present at the gate photomultiplier. The light intensity variation across a 250 μm width of the MCV is only a few percent so that the peak mean signal amplitude for a particular particle diameter can be assumed to be a function only of the direction normal to the optical axis. This greatly simplifies the data inversion and measurements with the gate photomultiplier showed good agreement with those obtained using flash photography for experiments using both glass particles and dilute kerosene sprays.

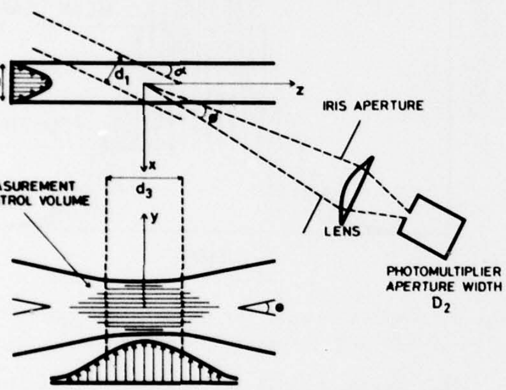


Fig. 5 Laser anemometer optical system showing measurement control volume with 'off-axis' collection for particle sizing[12]

The optical system shown in Fig. 5 is an off-axis forward-scatter mode with a narrow vertical slit photomultiplier aperture[12,13]. Off-axis collection reduces the dimensions of the region in which particles produce scattered light at the collecting photomultiplier, so that the effective length of the MCV is reduced. A collection angle of 6.8^{o} was selected[12,13] to preserve signal-to-noise ratios sufficiently high to obtain accurate velocity measurements and yet large enough to produce a significant reduction in the length of the MCV in which particles are detected. A vertical slit aperture, 85 μm wide, resulted in signals being accepted in a diagonal 230 μm wide slice of the MCV. The reduction in dimensions of the MCV is not as great as can be achieved by using the gate photomultiplier at 90^{o}, but the off-axis geometry has the advantage of eliminating the requirement of a second photomultiplier. This off-axis geometry enabled high particle number densities of at least $10^{10}/m^3$ to be measured without the statistical probability of there being more than one particle being measured at the same time. This density limit is sufficiently high for most low-medium throughput fuel sprays, except very close to the atomiser. Details of the optical and signal processing system and the methods used for analysing the data are described in more detail in Refs. 12 and 13.

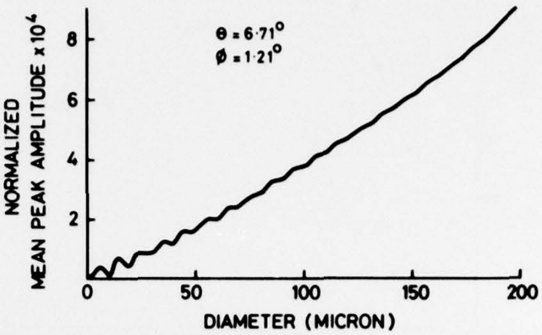


Fig. 6 Mean peak amplitude E_{p_o} of Doppler signal as function of particle diameter[13]

Figure 6 shows the variation of mean peak amplitude as a function of particle diameter for a beam angle of 6.71^{o} and a collection angle of 1.21^{o}. This shows that, for particles larger than the fringe spacing, in the range 30 - 200 μm, a one-to-one relationship between peak signal and size is obtained. This relation is different for transparent and opaque spheres, so that calculations and calibrations require to be made, based upon the optical properties of the particles.

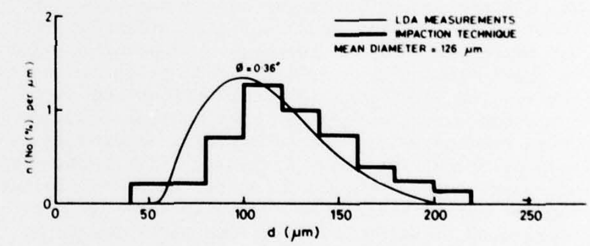


Fig. 7 Comparison of size distributions measured by laser anemometer (LDA) and impaction technique[11]

Figure 7 shows a comparison of size distribution measurements made by the laser anemometer with those made by impaction techniques. Figure 8 shows comparisons of particle size distributions measured in kerosene sprays by the laser anemometer and spark photographic techniques. In the impaction techniques, small particles are deflected around the impactor and inaccuracies arise in analysis of dimensions of individual impactions. In the photographic technique, inaccuracies arise in determination of whether the particles are in focus. The statistical averaging procedures used in the impaction, photographic and laser anemometer measurements are not the same, so that complete agreement is not found in particle size distributions obtained with these various techniques. The laser anemometer has the advantage of being a noninvasive, high

frequency response system, which allows simultaneous measurement of particle size and velocity, which can be processed and analysed by digital computer.

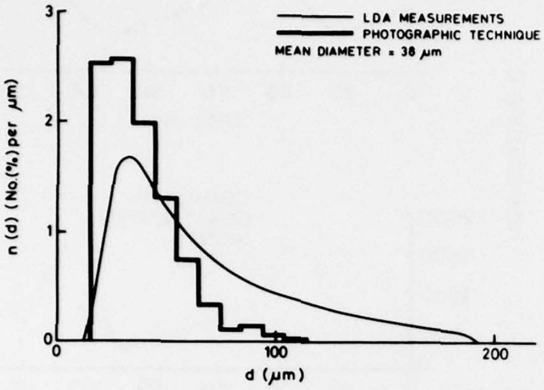


Fig. 8 Comparison between size distributions measured in kerosene spray by laser anemometer and spark photography[11]

4. Gas Temperature Measurement by Computer Compensated Thermocouple

Fine wire thermocouples can be used for making measurements of gas temperature in multiphase reacting flow systems. The first requirement for the use of such a thermocouple is that it should be able to survive the direct impaction of liquid droplets or solid particles; the selection of the minimum wire diameter is governed by this criterion. The measurement of temperature as a function of time in an unsteady flow field using a thermocouple requires knowledge of the time constant, which is a function of parameters governing the rate of heat transfer from the thermocouple bead to its environment. These parameters include the physical properties of the thermocouple bead, physical properties of the gas; temperature, concentration and flow fields in the vicinity of the probe. When the thermocouple is used for measurement of temperature as a function of time, the frequency response of the instrument can be substantially increased by compensating for the thermal lag as the thermocouple bead adjusts to the temperature of the environment. This compensation can be made by electrical analog but there is a fundamental limit to the frequency response of electrically compensated thermocouples and there are major signal-to-noise ratio problems.

In order to make measurements of variation of temperature in both space and time in flames laden with liquid fuel droplets and solid particles, a computer compensated thermocouple has been developed at Sheffield University[14]. Platinum-platinum rhodium and iridium-iridium rhodium thermocouples are constructed from fine wires with diameters between 25 and 75 μm. Figure 9 shows the system used for automatic derivation of thermocouple response characteristics and the digital processing of the thermocouple signal. Impulsive heating is applied repeatedly to the wire to produce a step-change in temperature, followed by decay as a function of time.

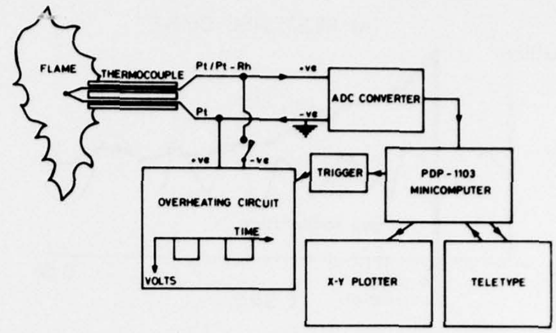


Fig. 9 System for pulsed heating and digital processing of micro-thermocouple signals[14]

A dc heating current is applied, for a time of the order of 10^{-2}s, and then switched off. The signal is recorded by the computer and an algorithm in the program converts the thermocouple emf into temperature by measuring the thermo-electric characteristics of the junction. This measured decay curve is generally concealed by the local temperature fluctuations in the flame, so that it cannot be used to accurately derive a local time constant for the thermocouple. This is indicated by the top curve in Fig. 10. This problem is solved by repeating the procedure 100 to 1000 times, depending on the magnitude of the local temperature fluctuations, and taking an ensemble average of the signals by adding each decay curve with time measured relative to the time at which the heating current is removed. A range of thermocouple configurations has been investigated in both nonburning and burning flows and the effects of varying parameters such as the overheating time and the number of 'overheatings' has been studied. The output from the thermocouple is recorded directly on a PDP-1103 mini-computer in conjunction with a Teledyne Philbrick ADC. The combination allows the rapid logging of thermocouple emf at a rate of 2000 readings per second. Figure 11 shows the temperature history in a propane/air diffusion flame before and after compensation by the computer for a thermocouple with a time constant of 17 ms.

The digital processing technique is capable of applying additional corrections if these are found to be necessary; for example, radiative heat transfer and catalytic effects. The digital processing provides vastly increased flexibility, compared with analog methods and also provides improved signal-to-noise ratios. When thermocouples are introduced into sprays in hot gas environments, the effects of the droplets on the temperature measurement vary according to the density of the spray. In regions of high density, there is a high probability of droplets hitting the thermocouple bead, where thay can cause an instantaneous reduction in temperature and may, in the extreme, remain on the bead, forming a film. In many spray systems, however, the density of the spray is such that the probability of a particle hitting the thermocouple bead is small and the time during which measurements are perturbated by droplets is small, compared to the total time during which measurements are made. Hence, it is possible to make measurements of the gas temperature, taking into account the perturbation due to the presence

increased number density of droplets.

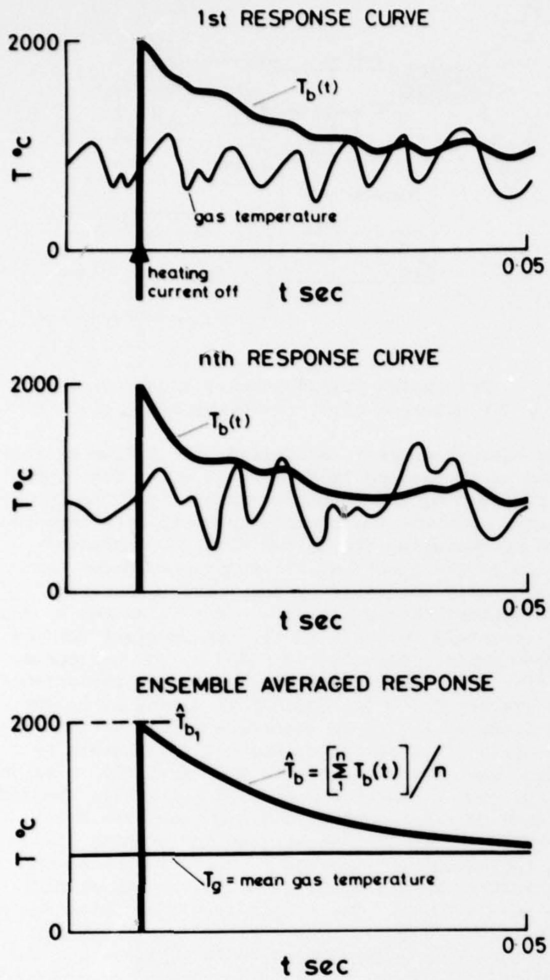


Fig. 10 Derivation of thermocouple response characteristics in a turbulent flame by ensemble averaging of multiple-pulse heating[14]

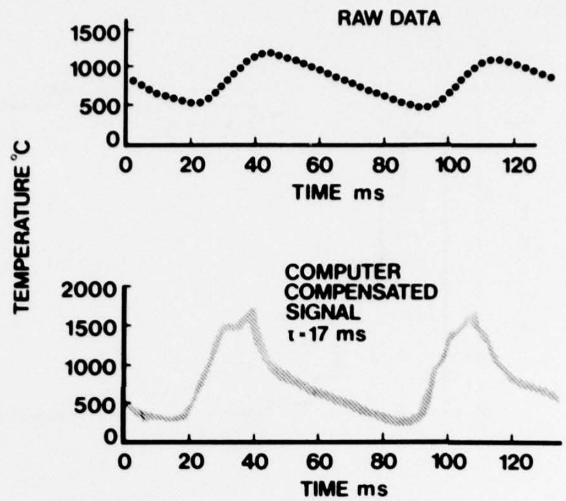


Fig. 11 Time history of temperature variation in propane/air flame as measured by thermocouple with computer compensation[14]

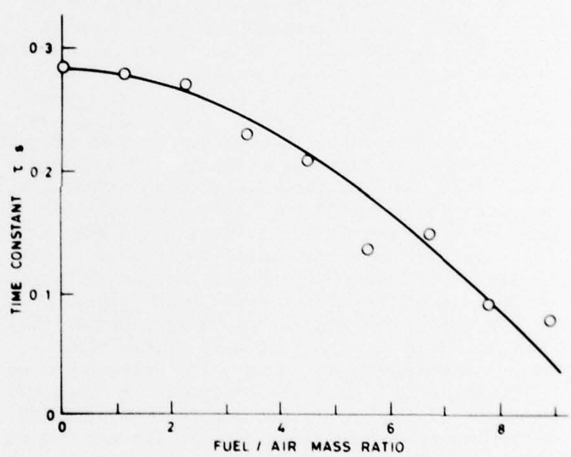


Fig. 12 Time constant of a thermocouple, measured by electrically overheating in the centre of a kerosene spray, as a function of fuel/air mass ratio[22]

of droplets.

In general, measurement of mean, rather than fluctuating temperature, is not sensitive to the precise response characteristics of the thermocouple. Measurements with thermocouples in sprays show that, apart from the case of very dilute sprays, the measured local mean temperature is intermediate between the local gas temperature and the temperature of the droplets. The thermocouple bead is effectively spray-cooled and the magnitude of this cooling is dependent on the local spray density, droplet sizes and velocities. When droplets impinge on the thermocouple bead and produce a thin film of liquid, the additional convective heating caused by this film can be recognized by an observed reduction in the measured thermocouple time constant. Figure 12 shows the time constant of a thermocouple, measured by electrical overheating in the centre of a kerosene spray as a function of the fuel/air mass ratio. This shows that the time constant decreases with increasing mass flow rate of liquid, which results in an

It was found that, when 25 μm thermocouples were inserted in kerosene sprays with droplets having sizes up to 200 μm and moving at velocities up to 40 m/s, they were not damaged. The presence of large droplets of heavy fuel oil or solid fuel particles will require more robust thermocouples in dense spray regions. The *in situ* measurement of time constants allows thermocouples to be used in these hostile environments for measurement of gas temperature variation with time. In addition to the temperature measurement, the measurement of time constant can also be exploited as a diagnostic technique in fuel sprays, to provide an indication of local spray density.

5. Measurements in Spray Flames

Measurements have been made in spray flames at Sheffield University over a period of twelve years. These have been reported and reviewed in Refs. 15 - 26.

higher than those for the small droplets. This demonstrates that the relatively small droplets lose most of their momentum soon after leaving the nozzle exit, due to their higher drag/inertia

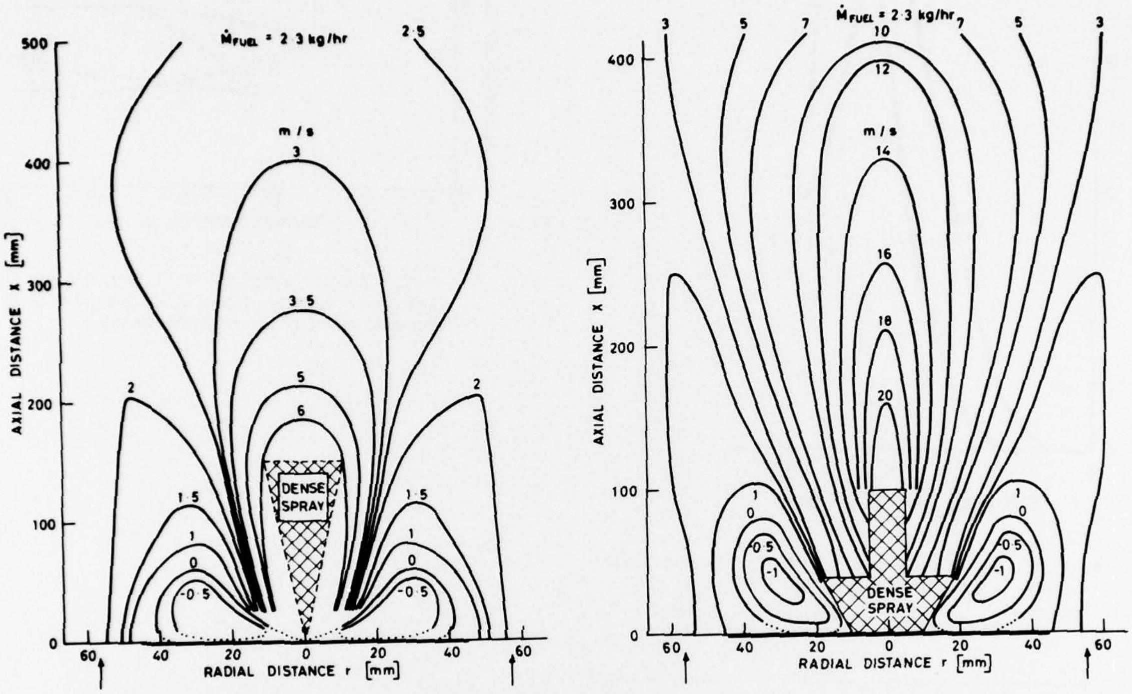
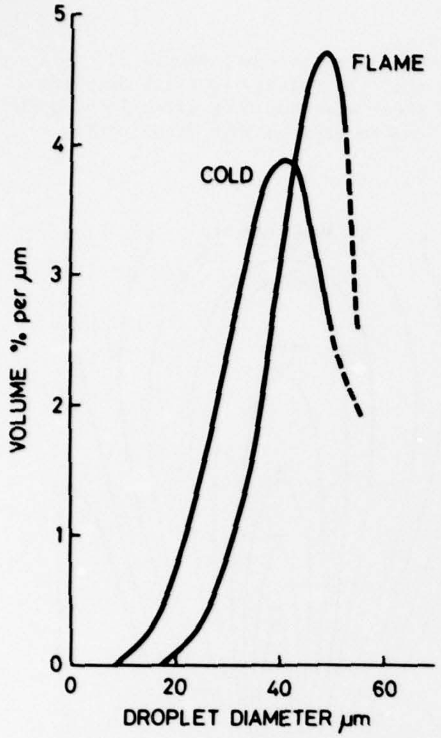


Fig. 13 Isovelocity lines in: a) isothermal spray; and b) spray flame, as measured by laser anemometer with frequency shift for reverse flow measurement[21]

Figure 13 shows an example of velocity measurements made by laser anemometer in a twin-fluid atomised kerosene spray under burning and nonburning conditions. Frequency shift in the laser anemometer allowed measurements to be made of reverse flow in the recirculation regions in the wake of the stabilizer disk. Significant increases in mean velocity, both in the forward and reverse flow directions, were found as a result of combustion (Refs. 16,20,21). In these measurements, no distinction could be made between the velocity of particles with different sizes. This led to the development of the laser anemometer for simultaneous measurement of particle size and velocity. Figure 14 shows the temporal size distributions for measurements made at the same position in cold and burning kerosene sprays by laser anemometer[12,13]. The cold spray was found to have a wider size distribution over the size range measured between 15 and 50 μm. These changes can be explained due to the preferential evaporation of small droplets, leading to total evaporation of the smallest droplets with a residue of larger droplets. The calculated local volume flux of droplets after ignition was found to be greatly reduced, due to combustion and evaporation. The mean droplet velocity and the variance of droplet velocity are shown as functions of droplet diameter in Fig. 15. These results show that, for the cold spray experiments, the mean velocities of larger droplets are

ratios, but the larger droplets are less affected because of their lower drag/inertia ratios. These measurements demonstrate the capability of the laser anemometer to measure local particle/gas velocity differentials, from which local Reynolds numbers and drag coefficients can be determined under conditions of vaporization and burning.

Figure 16 shows concentration profiles in an airblast atomised spray flame, measured by using a quartz micro-probe and analysing the gases by chromatography. Radial gas concentration measurements for CO_2, H_2, O_2, CH_4 and CO, with corresponding temperature profiles, are shown at two axial distances in the spray flame. Gas concentration and temperature variation along the centreline of the spray flame are shown in Fig. 17. These measurements showed that burning takes place at the outer periphery of the spray and that, within the spray, both oxygen concentrations and temperature levels are low.



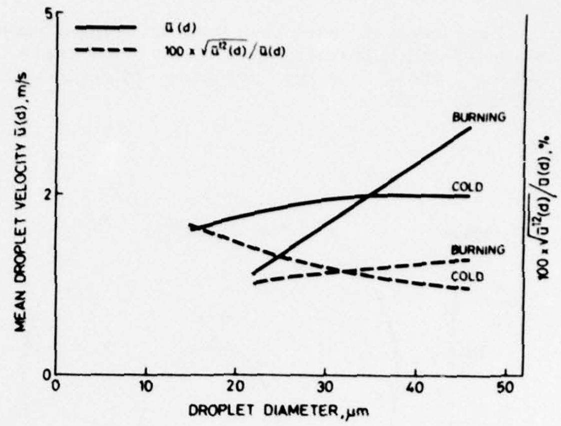


Fig. 15 Mean and rms droplet velocity measured in kerosene sprays under cold and burning conditions by laser anemometer[12]

Fig. 14 Particle size measurement by laser anemometer in cold and burning kerosene sprays[12]

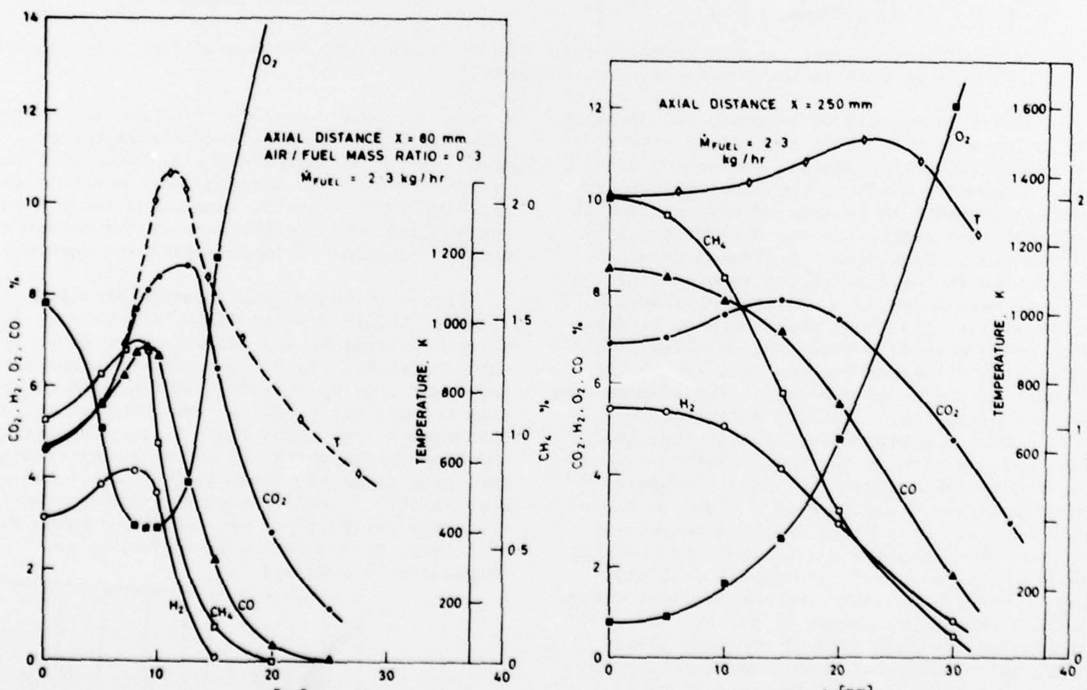


Fig. 16 Temperature and gas concentration profiles in spray flame at axial distance 80 and 250 mm[21]

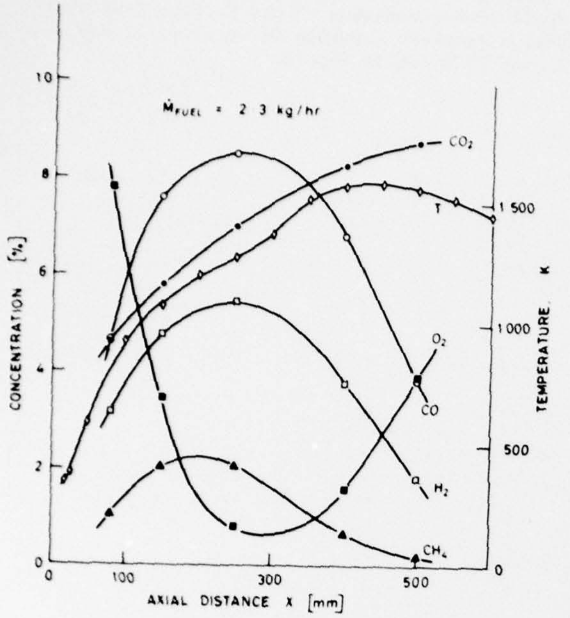


Fig. 17 Temperature and gas concentrations along the axis of a spray flame[21]

6. Future Developments

Further developments require to be made on all the diagnostic techniques described in this paper before routine measurements can be made in practical combustors. A steady evolution from the current use of probes to noninvasive laser diagnostic techniques can be expected. Because of the higher expense and complexity of laser diagnostic techniques, they will remain principally research instruments for use in fundamental studies.

Single pulse coherent anti-Stokes Raman spectroscopy is currently the most promising diagnostic technique for noninvasive laser probing of luminous and particle flames. CARS signals are several orders of magnitude larger that those for spontaneous Raman scattering. CARS signals are coherent, so that all of the CARS radiation can be collected. CARS radiation can be collected in an extremely small solid angle, so that discrimination can be made against background luminosity and laser-induced particulate interferences, such as incandescence and fluorescence. The use of high energy frequency-doubled neodymium pump lasers with spectrally broadband laser pumped Stokes dye lasers and optical spectrum analysers, allows measurement of major species concentration and temperature measurements to be made by CARS; minor species and radical concentrations can be measured by single pulse fluorescence. These techniques have been tried and proven in luminous flames in the presence of soot particles; further developments are required before they can be used in flames laden with solid and liquid fuel particles.

In the long-term future, it can be envisaged that particle size, temperature, velocity and direction, together with gas temperature, velocity and species concentration will all be measured by laser optical techniques with on-line digital recording, so that the complete mapping of combustors can be made automatically.

Acknowledgements

The author wishes to thank Drs. Yule, Taylor and Ungut and the research students, who have been responsible for making the measurements reported in this paper. Financial support has been provided by the Sçience Research Council, Office of Naval Research (Project SQUID), NASA and the Air Force (AFOSR).

AFOSR-77-3414

References

1 Mellor, R., Chigier, N. A. and Beér, J. M., 'Pressure Jet Spray in Air Streams', Am. Soc. Mech. Eng. Paper No. ASME 70-GT-101, 1970.

2 Mellor, R., Chigier, N. A. and Beér, J. M., 'Hollow-Cone Liquid Spray in Uniform Air Stream', Combustion and Heat Transfer in Gas Turbine Systems, pp 291-305, E. R. Norster (Ed.), International Symposium Series, II, Pergamon Press, 1971.

3 McCreath, C. G., Roett, M. F. and Chigier, N. A., 'A Technique for Measurement of Velocities and Size Particles in Flames, J. Phys. E: Scientific Instruments 5, 601, 1972.

4 Chigier, N. A. and Roett, M. F., 'Twin Fluid Atomizer Spray Combustion', Am. Soc. Mech. Eng., ASME Paper No. 72-WA/HT-25, 1972.

5 McCreath, C. G. and Chigier, N. A., 'Liquid-Spray Burning in the Wake of a Stabilizer Disc', Fourteenth Symposium (International) on Combustion, 1355-1363, The Combustion Institute, 1973.

6 Chigier, N. A., Makepeace, R. W. and McCreath, C.G., 'Aerodynamic Interaction between Burning Sprays and Recirculation Zones', Combustion Institute European Symposium, 577-582, F. Weinberg, (Ed.), Academic Press, 1973.

7 Chigier, N. A., 'Velocity Measurements of Particles in Sprays', Flow - Its Measurement and Control in Science and Industry, 1, 823-832, R. B. Dowdell (Ed.), Instrument Society of America, Pittsburgh, 1974.

8 Chigier, N. A., McCreath, C. G. and Makepeace, R. W., 'Dynamics of Droplets in Burning and Isothermal Kerosene Sprays', Combust. Flame, 23, 11, 1974.

9 Yule, A. J., Chigier, N. A. and Cox, N. W., 'Measurement of Particle Sizes in Sprays by the Automated Analysis of Spark Photographs', Particle Size Analysis, 61-73, Heyden Press, 1978.

10 Yule, A. J., Chigier, N. A., Atakan, S. and Ungut, A., 'Particle Size and Velocity Measurement by Laser Anemometry', AIAA J. Energy, 1, 220, 1977.

11 Ungut, A., Yule, A. J., Taylor, D. S. and Chigier, N. A., 'Particle Size Measurement by Laser Anemometry', AIAA J. Energy, 2, 1978.

[12]Chigier, N. A., Ungut, A. and Yule, A. J., 'Particle Size and Velocity Measurements in Flames by Laser Anemometer', Seventeenth International Symposium on Combustion, Leeds, 1978.

[13]Chigier, N. A., Ungut, A. and Yule, A. J., 'Particle Sizing in Flames with Laser Velocimeters', Third International Workshop of Laser Velocimetry, Purdue University, 11-13 July 1978, Hemisphere Press.

[14]Yule, A. J., Taylor, D. S. and Chigier, N. A., 'Thermocouple Signal Processing and On-Line Digital Compensation', AIAA J. Energy, 2, 223-231, 1978.

[15]Chigier, N. A. and McCreath, C. G., 'Combustion of Droplets in Sprays', Acta Astronautica, 1, 687, 1974.

[16] Chigier, N. A. and Styles, A. C., 'Laser Anemometer Measurements in Spray Flames, Second European Symposium on Combustion, 563-568, 1975.

[17]Chigier, N. A., 'Burning Spray Measurements', Combustion Measurements, 379-383, R. Goulard (Ed.), Academic Press, 1976.

[18]Chigier, N. A., 'The Spray Region and the Combustor Environment', Combustion Measurements, 406-411, R. Goulard (Ed.), Academic Press, 1976.

[19]Chigier, N. A., 'The Atomization and Burning of Liquid Fuel Sprays', Prog. Energy Combust. Sci., 2, 97, 1976.

[20]Chigier, N. A. and Styles, A. C., 'Velocity of Droplets in Kerosene Spray Flames', Workshop on Laser Anemometry, 399-416, German-French Research Institute (ISL), 1976.

[21]Styles, A. C. and Chigier, N. A., 'Combustion of Air Blast Atomized Spray Flames', Sixteenth Symposium (International) on Combustion, 619-630, The Combustion Institute, Pittsburgh, 1977.

[22]Chigier, N. A., 'Instrumentation Techniques for Studying Heterogeneous Combustion', Prog. Energy Combust. Sci., 3, 175, 1977.

[23]Chigier, N. A. and Styles, A. C., 'Temperature Concentration and Velocity Measurements in Fuel Spray Free Flames', Advances in Chemistry Series, 166, 111-125, American Chemical Society, 1978.

[24]Chigier, N. A. and Yule, A. J., 'Vaporization of Droplets in High Temperature Gas Streams', Proc. International Conference on Physical Chemistry and Hydrodynamics, University of Oxford, July 1977, Hemisphere Press Publishing Corp., 1978.

[25]Chigier, N. A., 'Spray Combustion', Workshop on Modeling of Combustion in Practical Systems. Department of Energy, Division of Power Systems, Los Angeles, January 1978.

[26]Chigier, N. A., 'Spray Diagnostics', Project SQUID (ONR), Workshop on Gas Turbine Combustor Design Problems. Purdue University, 31 May - 1 June 1978, SQUID Report.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR TR- 79-0657	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MEASUREMENT IN MULTIPHASE REACTING FLOWS - A REVIEW		5. TYPE OF REPORT & PERIOD COVERED INTERIM
		6. PERFORMING ORG. REPORT NUMBER ~~79-0082~~
7. AUTHOR(s) NORMAN A. CHIGIER		8. CONTRACT OR GRANT NUMBER(s) AFOSR-77-3414
9. PERFORMING ORGANIZATION NAME AND ADDRESS UNIVERSITY OF SHEFFIELD CHEMICAL ENGINEERING & FUEL TECHNOLOGY DEPARTMENT SHEFFIELD, S13JD, ENGLAND		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2308A2 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BLDG 410 BOLLING AIR FORCE BASE, D C 20332		12. REPORT DATE Jan 79
		13. NUMBER OF PAGES 11
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 2308 A2		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Aerospace Sciences Meeting, 17th, New Orleans, LA 15-17 Jan 1979

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

SPRAY FLAMES
MULTIPHASE REACTING FLOWS
COMBUSTION DIAGNOSTICS
SPARK PHOTOGRAPHY
LASER ANEMOMETRY
HIGH RESPONSE THERMOCOUPLES
PARTICLE SIZE AND VELOCITY
GAS PHASE CHROMATOGRAPHY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A survey is presented of diagnostic techniques and measurements made in multiphase reacting flows. The special problems encountered by the presence of liquid droplets, soot and solid particles in high temperature chemically reacting turbulent environments are outlined. The principal measurement techniques that have been tested in spray flames are spark photography, laser anemometry, thermocouples and suction probes. Spark photography provides measurement of drop size, drop size distribution, drop velocity, and angle of flight. Photographs are analyzed automatically by image analyzers. Photographic techniques are reliable, inexpensive

DD FORM 1 JAN 73 1473

400 047

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

and proved. Laser anemometers have been developed for simultaneous measurement of velocity and size of individual particles in sprays under conditions of vaproization and combustion. Particle/gas velocity differentials, particle Reynolds numbers, local drag coefficients and direct measurement of vaporization rates can be made by laser anemometry. Gas temperature in sprays is determined by direct 'in situ' measurement of time constants immediately prior to measurement with compensation and signal analysis by micro-processors. Gas concentration is measured by suction probes and gas phase chromatography. Measurements of particle size, particle velocity, gas temperature, and gas concentration made in air-blast and pressure atomized liquid spray flames are presented.